



APPLICATION OF ROAD SEDIMENT MODELS TO NATURAL
AND SIMULATED RAINFALL-RUNOFF SITES

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AUTHORIZATION

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ABSTRACT

This report details testing and refinement of quantitative road sediment yield models. The models being tested were previously presented but had not been verified with field data because adequate data were unavailable. Through the efforts of the United States Forest Service, Region 8 National Forest in Atlanta, Georgia and the Coweeta Hydrologic Laboratory located near Franklin, North Carolina some field data from natural rainfall events have been collected and made available for use.

In addition, simulated rainfall (rainulator) studies on roads in Montana and Idaho have provided data for testing the surface erosion component of a simplified road sediment yield model. This data was supplied by the U.S. Forest Service, Intermountain Forest and Range Experiment Station, Bozeman, Montana.

Results of the applications indicate that the models can reproduce the measured values. However, there is some concern that the measured values may be in error for many uncontrolled reasons. In spite of data uncertainties, the models seem to represent the controlling processes governing erosion from roadway surfaces.

INTRODUCTION

GENERAL

Quality of runoff water from forest lands can be severely degraded by sediments eroded from forest roads. Logging roads are often major sources of sediment production, especially on steeply sloping lands. Significant quantities of sediment delivered to nearby channels may cause adverse impacts on aquatic and riparian systems, reduce channel capacity, and increase flood hazards. A properly built and maintained road with adequate sediment controls can effectively reduce sediment yields and decrease erosion impacts on the downstream channels.

Effective evaluation of alternative routes and designs of road cross sections, road gradients and surfaces, cut slopes, embankments, and spacings of cross drains requires a method to predict sediment yields. In addition, prediction of water and sediment discharges is necessary for determining sediment control measures either within the buffer strip between the road and stream or in channels.

Because the physical processes governing erosion from roads are very complicated, previous studies have utilized a statistical interpretation of observed erosion data. The Universal Soil Loss Equation developed by the U.S. Agricultural Research Service is an example of the method used in these types of studies. However, it is difficult to predict the erosion rate associated with various design alternatives using statistical methods because the methods are based on the assumption of homogeneity in time and space. In spite of the complexity of the physical processes governing soil erosion, numerical modeling of the process systems is a realistic way to estimate the time and space dependent (changes with design alternatives) sediment yield from roads.

Research has resulted in the formulation of complex and simplified numerical physical process models that simulate erosion from roads (Simons, Li, and Shiao, 1977 and Simons, Li, Ward, and Shiao, 1978). Many processes in these road sediment models, such as a raindrop soil detachment, interception, infiltration, overland surface flow routing, and sediment transport, are similar to those in the watershed surface erosion model (Simons, Li, and Stevens, 1975). However, in the road sediment models, channel routing takes place in ditches and culverts. The complex model has been tested using limited on-site soil erosion data, however, it only had limited validation using field data from roads due to the unavailability of such data (Scheer et al., 1977).

Through the efforts of the U.S. Forest Service Region 8 National Forest in Atlanta, Georgia and Forest Service personnel at the Coweeta Hydrologic Laboratory located near Franklin, North Carolina a data base has been developed from measured variables for two roadway sites. Runoff and sediment yields resulting from natural rainfall events were measured and provided to CSU for model testing.

However, because of the variability of the duration, magnitude, and distribution of the rainfall, and the physical constraints on the dimensions of the road segments, some measured events were not physically realistic. This is to be expected, particularly when dealing with cut and fill slopes because they usually have much smaller runoff volumes as compared to road surfaces. Such small runoff values are hard to measure and are frequently of the same magnitude as measurement errors. Because of the possible errors in the cut and fill slope data, only the road surface data from Coweeta was utilized for testing the complex road sediment model.

The simplified model was tested using simulated rainfall (rainulator) data from mine haul roads located in Montana and Idaho. This data was supplied by the Intermountain Forest and Range Experiment Station in Bozeman, Montana. The simulated rainfall data seemed more accurate than the natural rainfall data because tighter control on possible measurement errors existed in the planned experiments. However, even with controlled conditions, measurement errors and equipment malfunctions can create spurious results. Therefore, before data sets are used in model application they must be screened for inconsistent or unrealistic results. Only with adequate data can the models be reliably tested. This and future quantitative testing which covers a wide range of climatic and roadway conditions will provide the opportunity to evaluate performance of the models.

OBJECTIVES OF STUDY

The primary objectives of this study can be summarized as:

1. To help develop the data collection system used in supplying data at the Coweeta Hydrologic Laboratory.
2. To test the road sediment models for a variety of rainfall events including high intensity, short duration storms; low intensity, long duration storms; and simulated rainfall as available.
3. At some future date, to provide sample simulations for general soil, rainfall, and design conditions in order to develop road design and maintenance guidelines.

The only data constraints apparently realistic rainfall-runoff data for natural events was that collected from the road surfaces. Data from the cut and fill slopes for the natural events was inconsistent because of the low runoff volumes relative to rainfall and the mass wasting failures by mudflows. Both of these problems plus other mechanical difficulties discovered when checking the data indicated

that information from the cut and fill slopes would be difficult to use in modeling. Therefore, only road surface data was used for model applications for natural events. Even with this choice, some measured values were questionable as will be discussed later. Because the simulated rainfall experiments were conducted on road surfaces, only the road was used for model testing.

GENERAL MODEL FORMULATION

BACKGROUND

The natural processes of erosion and sediment yield are complex physical phenomena. A mathematical model that attempts to duplicate the processes involved was constructed based on the abstraction of the physical processes. The models are referred to as ROSED (ROad SEDiment) for the finite difference model and SIRSED (SImplified Road SEDiment) for the simplified model.

The basic concepts and assumptions of the models are presented in Simons et al. (1977) and Simons et al. (1978). These models operate using a timespace water and sediment routing procedure. The space increment of road erosion and sediment yield models is structured on a conceptual road prism. A typical road prism is considered to be composed of five individual but interconnected response units, and each response unit is assumed to be homogeneous with respect to its physical characteristics. A road prism (Figure 1) can be composed of: a cut slope, a fill slope, road surface, a collecting ditch, and a culvert. Similar to the watershed model (Simons et al., 1975), flow characteristics of the response units are categorized into three types: 1) overland flow, 2) ditch flow, and 3) culvert flow. The two models considered in this application are ROSED (ROad SEDiment) the finite difference version.

Water is the driving mechanism for erosion and sediment yield in the system. The physical processes considered are rainfall interception, infiltration, overland flow, channel flow, culvert flow, and sediment transport.

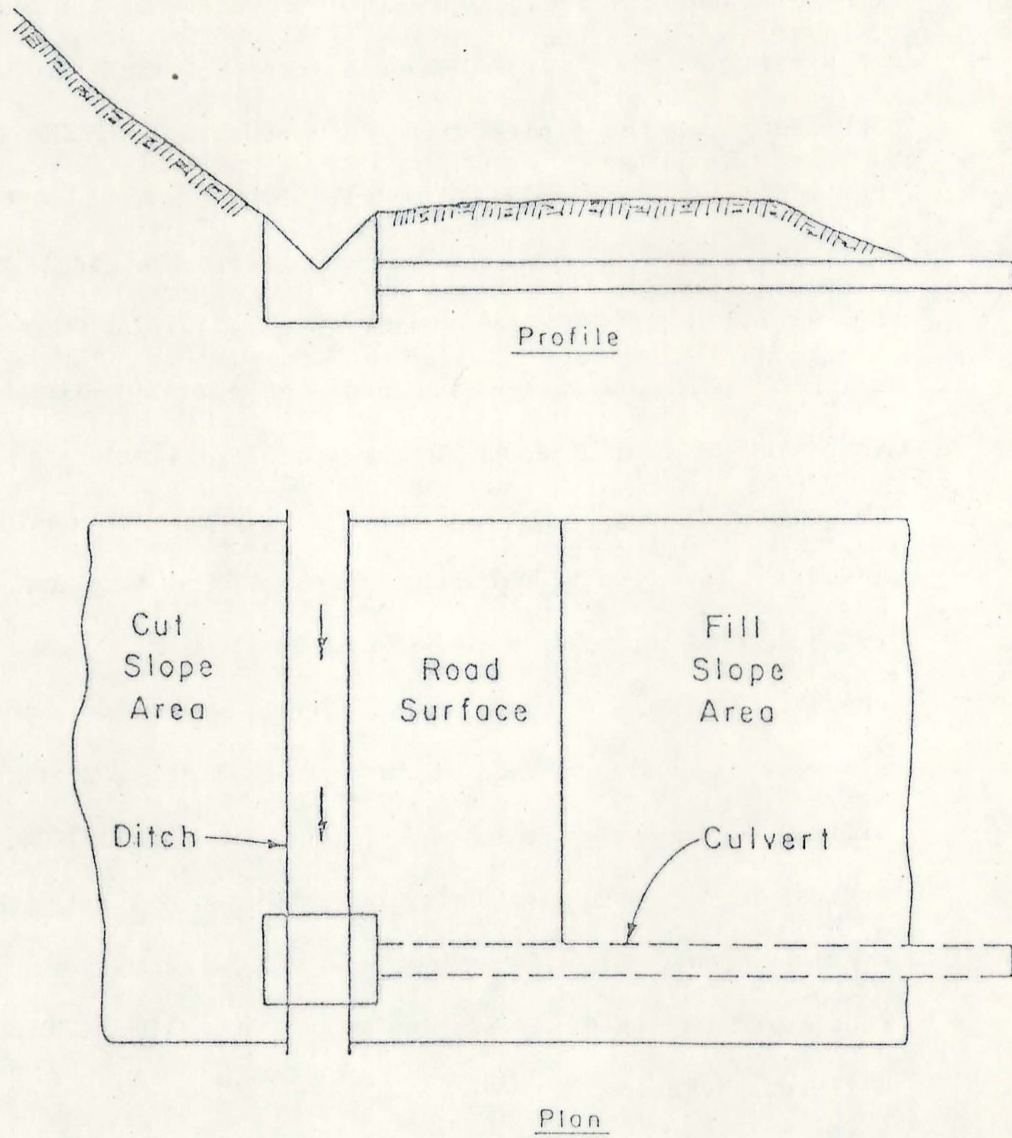


Figure 1. Typical road prism.

DATA NEEDS

Data for the models can be classified into the following general categories:

1. General Information. Includes the name or title of the problem, number of overland flow units, number of culvert flow units, number of ditch flow units, number of space increments, number of storms, number of particle sizes, and maximum number of iterations to reach a convergence criterion in estimating the water discharge simulation time increment and kinematic viscosity.
2. Computational Sequence. Includes the order of computation, (i.e., direction of flow between segments) upstream and lateral inflow response units, and the type of response units.
3. Roadway Characteristics and Geometry Data. Includes the type (plane, ditch, culvert) identification of the response units, length and slope of the response units, side slope for the ditch and diameter of the culvert, hydraulic conductivity in the wetted zone, average suction head, moisture content in the wetted zone, antecedent moisture content, canopy cover and ground cover density, and the intercepted volume of water by canopy and ground cover.
4. Flow Resistance Parameters. Includes grain resistance parameter, low and high overall resistance parameter, culvert resistance parameter (Manning's n), and parameters describing wetted perimeter-flow area relation.
5. Size Distribution. Soil particle sizes and distribution.
6. Sediment Routing Parameters. Includes coefficients used in the rainfall soil detachment and sediment transport equations.
7. Flow Detachment Coefficient. Used in computing amount of sediment detached by overland or ditch flow.

Precise determination of every input is not always necessary because the models are more sensitive to some inputs than others. However, realistic simulations do require reasonable estimates of the input variables. In addition some variable inputs are later calibrated i.e., adjusted to make the model simulations better match measured values.

APPLICATION TO NATURAL RAINFALL SITES

LOCATION

Coweeta Hydrologic Laboratory located near the town of Franklin in western North Carolina was established by the U.S. Forest Service in 1934 to study the effect of silviculture activities on water yield. This laboratory has jurisdiction over two creeks, Coweeta Creek and Dryman Fork, which have a total drainage area of 6,100 acres. Based on study needs of the area, the Coweeta Creek drainage area was divided into numerous smaller watershed units. In cooperation with Region 8 National Forest, Atlanta, Georgia data was made available for two road segments in this watershed. Physical dimensions of both road segments are summarized in Table 1. The sites are located at an elevation of about 3,600 feet, with the first site (site A) situated about 20 feet higher than site B. Both sites consisted of three segments of cut slope, fill slope, and road bed that were isolated from one another by soil berms and ditches.

SOIL

The residual soils in the Coweeta area are weathered from parent material classified as Carolina gneiss of pre-Cambrian age. These rocks include granite gneiss, mica gneiss, and mica schist. Generally, soil mantles are deep and porous as evidenced by the absence of significant overland flow. At elevations of 3,700 feet most of the soils are gray-brown podzols weathered from granite gneiss, or schist. The soils at lower elevations are a combination of red-yellow podzols, gray-brown podzols, and lithosol. Colluvial soils and alluvium are also found along some tributaries and the main stream in the valley floor. Except for the deeper colluvial and alluvial soils, soil depths

Table 1. Geometry of Coweeta sites.

Site A	Site B
Segment 734 Fill Slope	Segment 737 Fill Slope
Fill	Fill
width = 48.83 ft	width = 48.5 ft
slope length = 15.06 ft	slope length = 12.8 ft
slope = 80%	slope = 100%
Ditch	Ditch
width = 2.17 ft	width = 0.71 ft
depth = .83 ft	depth = 0.33 ft
slope = 8%	slope = 9%
length = 48.83 ft	length = 48.5 ft
Segment 735 Road Bed	Segment 738 Road Bed
width = 19.98 ft	width = 22.47 ft
length = 146.42 ft	length = 108.25 ft
slope = 7%	slope = 5%
Segment 736 Cut Slope	Segment 739 Cut Slope
Cut	Cut
width = 146.42 ft	width = 108.25 ft
slope length = 12.79 ft	slope length = 12.50 ft
slope = 100%	slope = 100%
Ditch	Ditch
width = .92 ft	width = 0.92 ft
depth = 0.38 ft	depth = 0.38 ft
slope = 5%	slope = 6%
length = 146.42 ft	length = 108.25 ft
Culvert	Culvert
diameter = 1.5 ft	diameter = 1.5 ft
slope = 10%	slope = 8%
length = 32.67 ft	length = 32.42 ft

generally vary from 36 to 60 inches. All of the soils have moderately high to high internal and external drainage.

CLIMATE

The Coweeta drainage area is characterized by abundant precipitation and moderate temperatures. Average annual total precipitation is about 80 inches. The mean annual average temperature is 55°F. Maximum summer temperatures higher than 94°F are rare.

Vegetation and Ground Cover

There was no vegetation cover for both sites when the first data collection period began in the spring of 1976. Grass was seeded on both cut and fill slopes on June 15, 1977. At the same time gravel was spread on road beds. At the first site, referred to as site A, about 4 inches of 3-inch size clean stone was spread on the road bed. At site B approximately 6 inches of crushed run gravel was spread on the road bed. Because of natural subsidence and vehicle weight, the gravel pavement packed down to a thickness of 3 to 4 inches. The simulations presented in this progress report for model testing are for pretreatment conditions and sediment yields. A sample simulation for a graveled road bed is also included.

INSTRUMENTATION

There was one continuous rainfall recording gage located about 1000 feet east of site A. A standard can precipitation gage was used to record the total precipitation. The time distribution of rainfall was assumed to be the same as the continuous recording gage but the recording gage precipitation was adjusted to that of the standard can. Precipitation was assumed to be uniformly distributed over the area, an assumption that may not be accurate. Water and sediments from cut

bank, road bed, and fill bank are collected separately. A galvanized steel rectangular shaped ditch is located at the bottom of the cut slope to collect all the water and sediment flow. This ditch drains into a 30" diameter stand pipe which is connected to an 18" diameter culvert. A galvanized steel rectangular shaped ditch was installed at the bottom of fill slopes to collect and convey the water and sediment flow. An inlet pipe was installed at the top of the fill slope to collect water and sediment flow from the road bed. The water and sediment outflows passed through flumes with attached stage recorders. Suspended sediment was measured with a Coshocton wheel sampler and splitter tanks. Because of low gradients in the ditch and culverts, sediment deposits accumulate and are subsequently removed by hand. These deposits are often ten times greater in weight than the measured suspended sediment yields.

SITE DESCRIPTIONS

Geometry of the Site

The geometry of the sites is fairly similar between segments (Table 1). A fill slope segment consists of a slope, a conveyance ditch, and measurement devices. The road beds are isolated by berms and have outflow points to the measurement devices. The cut slope is similar to the fill slope except water and sediment must also pass through a culvert before entering the flume.

Rainfall Data

A total of nine storms was provided by personnel at the Coweeta Hydrologic Laboratory for possible simulation. These storms exhibit a large variation in characteristics (Table 2). Six of the nine storms consisted of two or more distinct rainfall periods necessitating

Table 2. Storm Characteristics.

Storm Identification Date	Duration, Minutes	Depth, Inches	Peak One Minute Intensity, Inches per hour	Average Intensity Inches per hour
9/26/76A	187	0.29	1.87	.09
9/26/76B	57	0.35	3.62	.37
Total or Average	244	0.64		.16
11/28,29/76	1220	1.28	0.41	.06
2/24/77	210	1.16	4.08	.33
3/4 - 6/77A	180	1.37	1.45	.46
3/4 - 6/77B	645	0.98	0.38	.09
Total or Average	825	2.35		.17
3/11 - 12/77A	67	0.12	0.21	.11
3/11 - 12/77B	1657	3.66	12.60	.13
Total or Average	1724	3.78		.13
3/28 - 30/77A	289	0.43	0.16	.09
3/28 - 30/77B	992	3.32	6.18	.20
3/28 - 30/77C	103	0.62	1.67	.36
Total or Average	1384	4.37		.19
4/2 - 4/77A	286	1.86	4.58	.39
4/2 - 4/77B	355	2.82	10.46	.48
Total or Average	641	4.68		.44
6/6/77	44	0.5	3.36	.68
6/19/77A	80	0.73	3.08	.55
6/19/77B	8	0.40	5.45	3.00
Total or Average	88	1.13		.77

further division of the events for modeling purposes. Two storms 3/11-12/77 and 4/2-4/77 were multiple events. In the former storm the short precedent rainfall period was not simulated, but its assumed effects on initial soil moisture conditions were incorporated into the simulation of the second part of this storm. The latter event had two distinct rainfall sequences that were modeled separately. These storms also had different rainfall patterns as shown in Figure 2. This plot shows nondimensional volume (depth) versus nondimensional time. The 3/11-12/77 storm shows a delayed pattern as most of the rain falls in the latter part of the storm whereas the 6/6/77 storm has an advanced pattern because most of the rain falls in the beginning of the storm. Two parts of the 4/2-4/77 storm are intermediate indicating a mixed type of storm. The wide variety of storm characteristics among the recorded events permitted various choices for simulation.

Soil Data

Soil properties and particle size distributions were developed from data collected at Coweeta. The soils property data provided an initial point for calibration of the model. These values could then be adjusted as initial conditions changed.

Runoff Data

Water and sediment yields were provided for each surface. Preliminary screening of the data indicated that there were questionable values present. Of particular concern was the discrepancy between the measured water yield and the calculated rainfall volume falling on the cut and fill slopes. In almost every case the runoff was less than the rainfall entering the collector ditches. These discrepancies were reported to personnel at the Coweeta Laboratory who then recalibrated

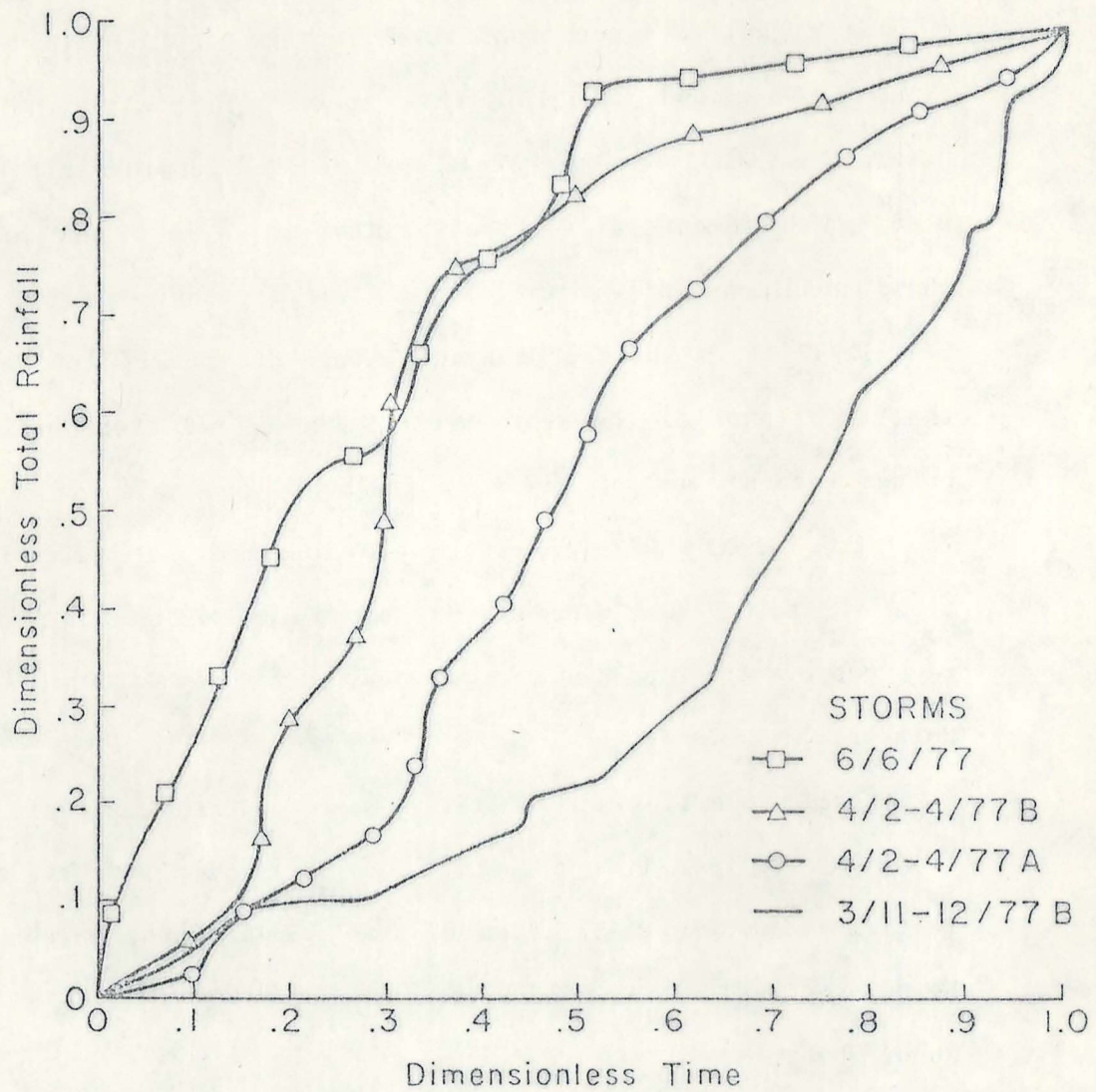


Figure 2. Rainfall accumulation compared with time for three storms.

their flumes. The resultant water and sediment yield adjustments were somewhat better but still left doubt as to the applicability of the data in model testing. There were a total of 54 event-surfaces in the original data set. Twenty-one of the 36 cut and fill slope event surfaces showed less runoff than what would fall in the collection trough. Two of 18 event surfaces for the roadbed (segment 738 for events of 4/2-4/77 and 6/19/77) indicated more runoff than rainfall. Because the majority of the cut and fill slope data was suspect, none of it was used in model testing. Of the roadbed data, segment 738 was chosen (personal communication with Lloyd Swift) as being a better surface for model application.

Model Application and Results

Three storms were initially chosen for adjusting ROSED. These were 9/26/76, 3/4/77, and 6/6/77. These were chosen because they showed reasonable water and sediment yields for the road surface. Using these storms a hydraulic conductivity was selected at about 0.20 inches per hour. Water yields for other storms were then predicted using the selected value modified for temperature. The results are shown in Figure 3. As this figure shows, there are some discrepancies that cause the 6/19 storms to be outside the $\pm 50\%$ bands ($\frac{1}{2}$ to $1\frac{1}{2}$ times). One possible explanation is that the assumed (no data available) antecedent moisture conditions were erroneous or again, measured water yield was incorrect. In general, though, the results are good but the need for a more refined data set is indicated.

Predicted sediment yields were matched against measured yields by adjusting the overland flow detachment coefficient. All storms were used in the adjustment to determine the time variant behavior of the

detachment coefficient. The model-predicted water was used to determine the yields from the roadbed. This approach may introduce error into the selection of D_{of} but it does indicate the relative change in D_{of} between storms. The calculated variation of the detachment coefficient is shown in Figure 4. As the figure shows, the detachment coefficient D_{of} is low in the fall and winter but increases dramatically during the spring and summer. Even though these are not calibrated values, they do show the change in the D_{of} caused by several factors including freeze-thaw, wetting and drying cycles, and road use. This result should be helpful in further studies for adjusting D_{of} values for the season of the year. A comparison of the model predicted and measured sediment yields is presented in Figure 5. As expected, the values are quite close because all of the values were individually adjusted.

In order to study transferability between sites, the model was tested using segment 735 (roadbed) data and the previously adjusted hydraulic conductivity and D_{of} values computed for segment 738. The results for the storms are presented in Figures 6 and 7. As these comparisons indicate, the predicted water yields are reasonable compared to the measured except for the 4/2 storm where equipment problems are suspected, and for 2/24 and 11/28 which were questionable for other reasons. Sediment yield comparisons (Figure 6) show that again the predicted values are reasonably close to the measured values. Differences do result from poor predictions of water yield which are reflected in the sediment yield.

Even with the apparent inconsistencies that have been found in the data base, the data seems adequate for limited qualitative testing of

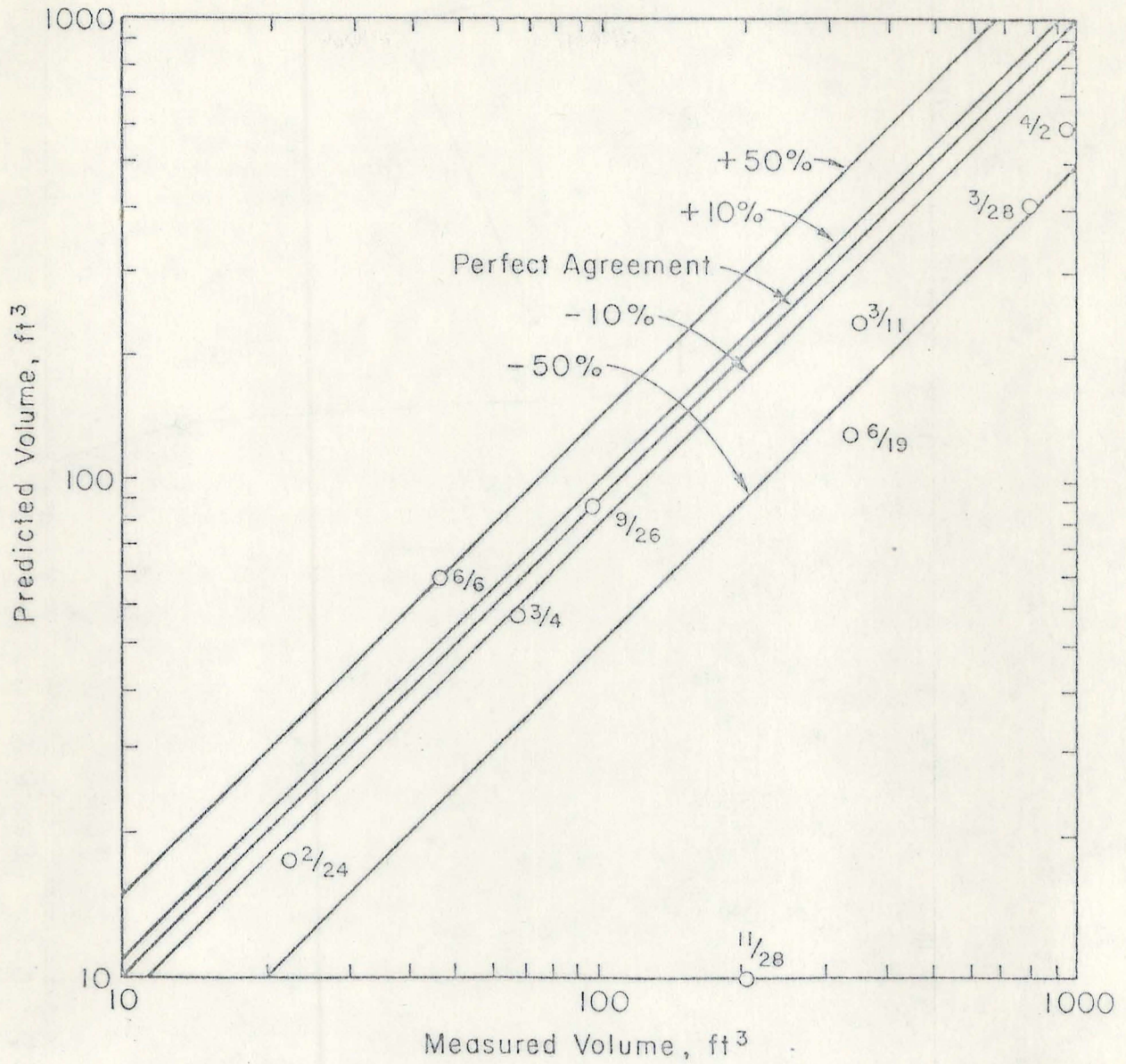


Figure 3. Predicted and measured water yields for segment 738.

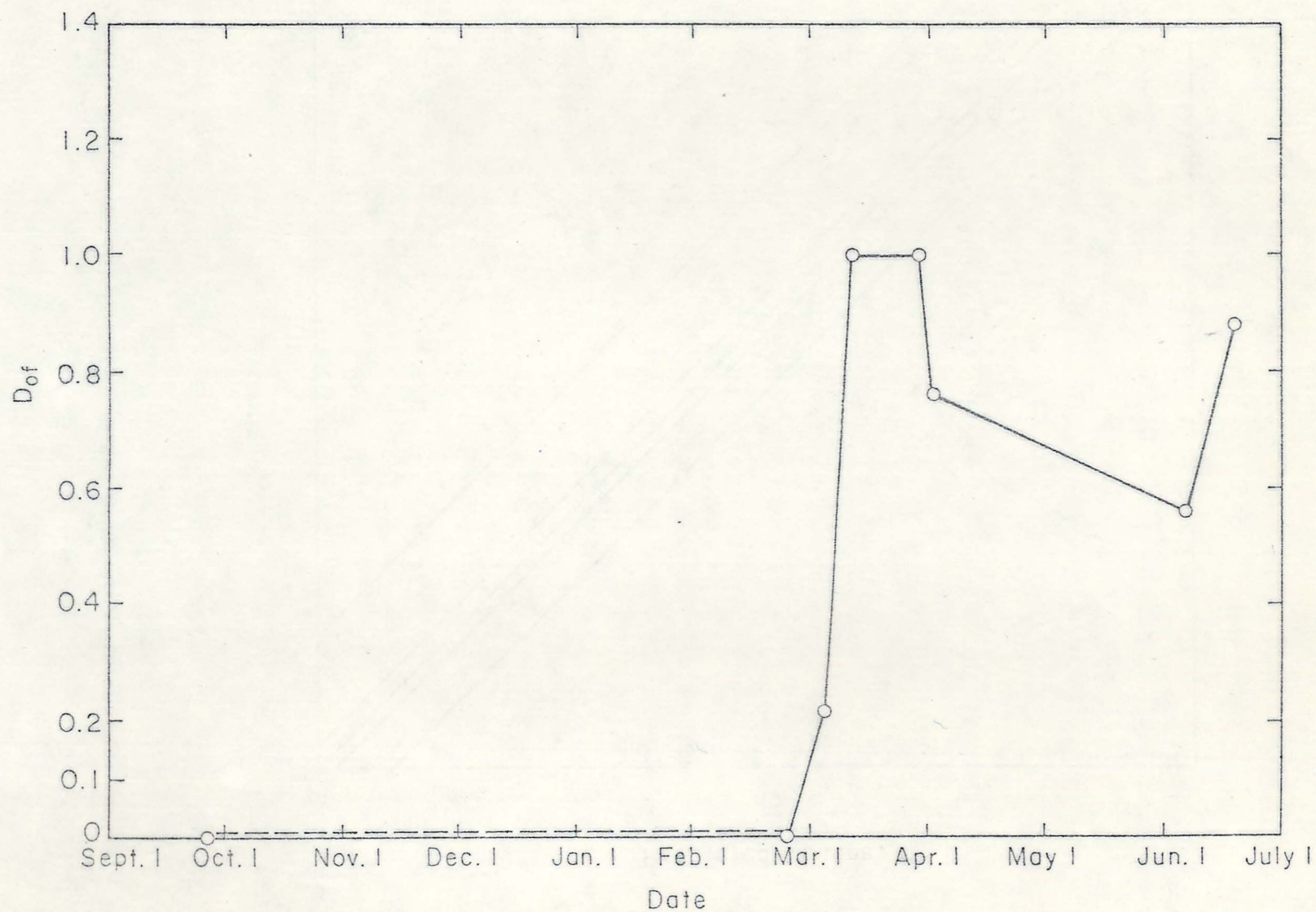


Figure 4. Change in calculated detachment coefficient with time.

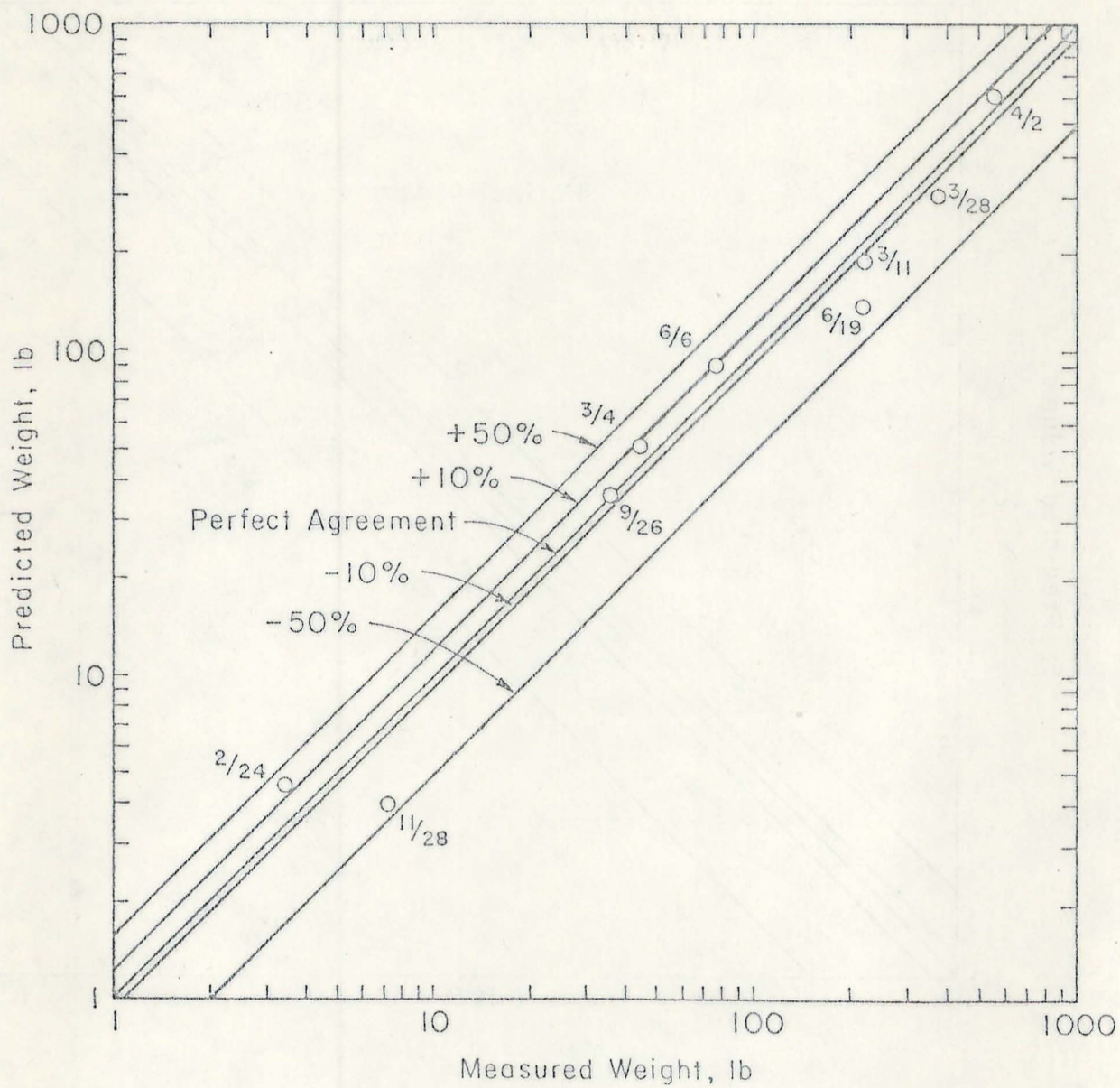


Figure 5. Predicted and measured sediment yields for segment 738.

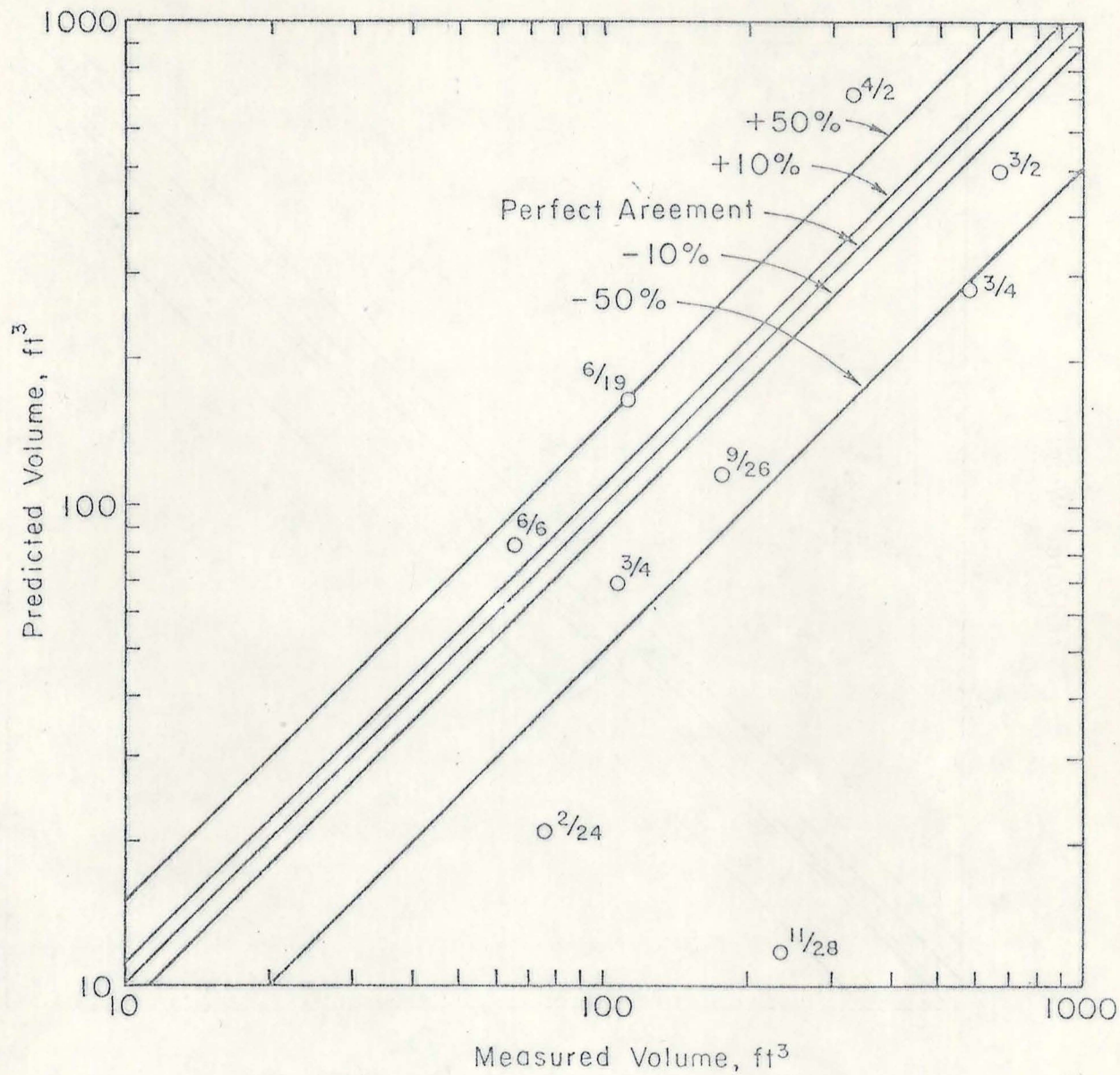


Figure 6. Predicted and measured water yields for segment 735.

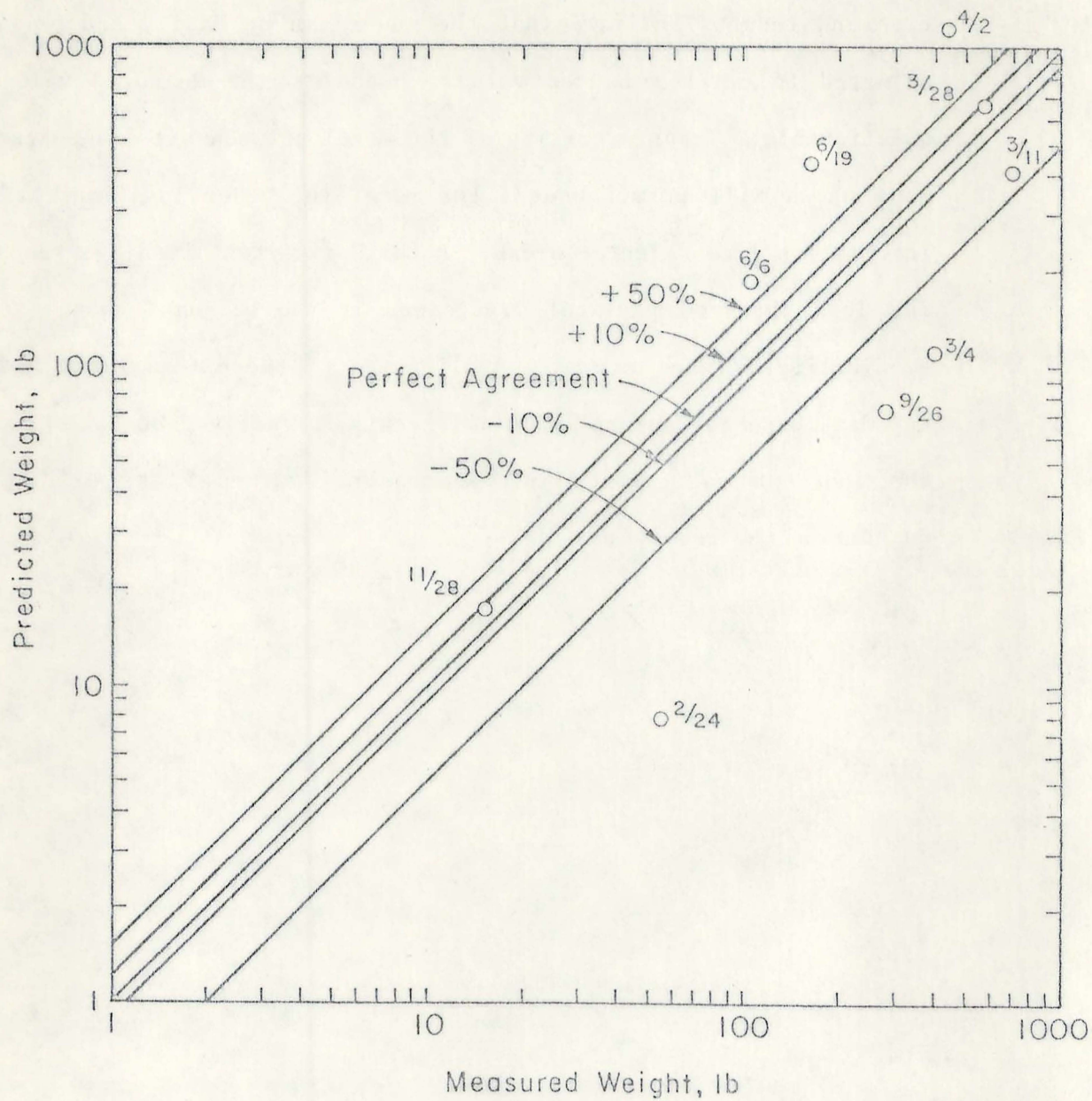


Figure 7. Predicted and measured sediment yields for segment 735.

the road sediment model. However, such tests are only semi-quantitative because of the unknown quality of the data. The application and results indicate that the model can be easily and reasonably adjusted to match measured values, but that the measured values are questionable. Transferability of the model between sites appears to be good which will permit use of the model for other locations based on information from selected areas. A third important finding, reconfirming long observed physical processes, is the seasonal change in soil erodibility between storms. Application of the mathematical model to the data base for natural rainfall events is fairly good but because of the inherent variability in the measured values it is difficult to quantitize the results.

APPLICATION TO SIMULATED RAINFALL

Data was acquired for rainfall-runoff experiments on road surfaces from Ed Burroughs and Eric Sundberg of the USDA Forest Service in Montana for mine haul roads. This information was screened and used to test the simplified water and sediment yield road model.

TEST SITES AND DATA

Test Sites

The test sites utilized were road sections in active mining areas in Montana and Idaho. Because of the priority of the data, each site and run is identified by a combination of letters and symbols as shown in Table 3. The letter or letters and the first number identify the road site, and the second number identifies the run designation. Run designation numbers of 2 or 3 indicate "wet" runs where the road was wetted by a previous experiment. Seven additional data sets for five mines were developed from the original 11 available data sets. These sets formed the basis for model testing. Even with controlled experiments, inherent variability eliminated some data sets.

Test Data

Data used in the simplified model can be grouped into geometric, soils, vegetation, rainfall, and sediment and water yields. Because the simplified model tests the road surface as a single plane, each surface was converted to that geometric form. Fortunately, such a form was representative of the test sections. Table 3 lists the geometric characteristics of the test sections.

Soils size data were provided as grain size analyses of "before run," "after run," and "runoff" samples. The before run samples were randomly collected from surface sweepings. Soil moisture and density

Table 3. Geometry of the Test Sites.

Site	Average Length of Section (ft)	Centerline Slope	Average Width (ft)	Area (ft ²)
C1-1	144.45	.031	33.04	4773
D2-2	76.83	.052	41.28	3171.2
D2-3	76.83	.052	41.28	3171.2
S1-1	122.00	.031	33.30	4062.5
S3-1	114.62	.055	32.34	3707.0
S3-2	114.62	.055	32.34	3707.0
SG2-1	174.11	.044	33.60	2490.0

readings were also collected before and after the runs. The before run size distributions were composited and plotted on log probability paper to obtain the median grain size D_{50} and gradation coefficient G as

$$G = \frac{1}{2} \left(\frac{D_{50}}{D_{15.9}} + \frac{D_{84.1}}{D_{50}} \right) \quad (1)$$

where $D_{15.9}$, D_{50} , and $D_{84.1}$ are the grain sizes at which 15.9, 50, and 84.1 percent, respectively, of the on-site soil samples are finer by weight. Soil porosity n is found from the specific gravity of the soil particles and the dry specific weight of the on-site soil as

$$n = 1 - \frac{\gamma_{\text{soil}}}{\gamma_w G_s} \quad (2)$$

where γ_{soil} is the dry bulk specific weight of the soil, γ_w is the specific weight of water, and G_s is the specific gravity of the soil particles. Soil saturation is found from the gravimetric water content of the soil w , specific gravity of the soil particles, and the void ratio e as

$$S = \frac{w G_s}{e} \quad (3)$$

where

$$e = \frac{n}{1-n} \quad (4)$$

In the simplified erosion model, the final saturation is assumed to be 1.0. Although initial and final water contents were provided, the difference between the initial and final was used to determine an adjusted initial value for use in the model. Runoff hydrographs and

rainfall rates were used to estimate soil infiltration parameters. In most experiments runoff reached a fairly steady rate before rainfall was terminated. This was not always the case and a distinct peak discharge was evident. In the former instance the steady rates were averaged to obtain a representative runoff rate, and in the latter case the peak rate was selected as representative. The difference between the representative runoff and rainfall rates was defined as a characteristic hydraulic conductivity. This characteristic hydraulic conductivity K_c was used to compute another parameter α that is a combination of soil porosity, initial saturation S_i , and potential capillary suction head ψ . The value of α was found from

$$\alpha = \left(\frac{i}{K_c} - 1 \right) i t_p = \psi n (1 - S_i) \quad (5)$$

$$\alpha = POTH * POROS * (1 - AMC) = .394$$

where i is the rainfall rate and t_p is the time to ponding (the time when runoff begins). The value of t_p can be estimated from the runoff hydrographs but was provided by observers for each experiment. Results of the on-site soil analyses and the hydrograph computations are presented in Table 4. As this table shows, there is a great variation between sites which helps demonstrate the transferability of the model. Several values presented in Table 4 should have further explanation. Typical experiments consisted of a "dry" initial run followed by "wet" subsequent runs. Dry runs have low S_i values while wet runs have high S_i values. These values are computed from soil moisture measurements and average dry bulk densities. The K_c values vary between D2-2 and D2-3, perhaps caused by using an averaged rainfall rate. It should be noted that in four data sets, the runoff rate exceeded the average rainfall rate, thus eliminating these sets from

Table 4. Computed and Estimated Soil Characteristics for Mine Haul Road Sites.

Site	Median Diameter D_{50} (mm)	Gradation Coefficient G	Specific Gravity of Sediment G_s	Soil Porosity n	Initial Saturation S_i	Difference Between Rainfall Rate and Representative Runoff Rate K_c (in/hr)	Computed α
C1-1	.34	13.74	2.61	.43	.26	.349	.394
D2-2	.35	10.86	2.65	.359	.99	.182	.371
D2-3	.35	10.86	2.65	.359	.99	.375	.159
S1-1	2.0	6.75	2.61	.22	.07	.549	.631
S3-1	1.4	14.42	2.65	.21	.23	.031	5.197
S3-2	1.4	14.42	2.65	.21	.99	.291	.191
SG2-1	3.0	4.79	2.74	.24	.07	.056	1.936

analysis. The large difference in K_c values for S3-1 and S3-2 is difficult to determine. At the D2 site it was also observed that initial runs infiltrated differently than subsequent runs. This was believed to be the result of the first run altering the soil surface and moisture conditions. Similar phenomena may be present at the S3 sites. Because of a lack of data, the S_i value for SG2-1 was estimated to be the same as S1-1. The values of α presented in Table 4 were estimated from the K_c values. Caution should be exercised if ψ is to be computed from α , S_i , and n since unrealistic answers may result. This is caused by the inherent difficulty in determining representative S_i and n values based on limited tests and averaged soil properties. Therefore, the value of ψ , although it has a definite physical meaning, may seem erroneous if it is calculated using estimated and average values of the other variables.

Characteristics of the rainfall, runoff, and sediment yield are presented in Table 5. Rainfall rates are averaged from several gages. The rainfall and runoff durations are rounded to the nearest minute, and the water and sediment yields are determined from integrating respective outflow hydro- and sedi-graphs. Because of the large sediment sizes (about the size of gravel), the road was assumed to have a flow resistance factor of about 400. Grain resistance was selected as 50 and kinematic viscosity as 1.05×10^{-5} ft²/sec. The sites were not vegetated.

APPLICATION AND RESULTS

After data analyses and development, the simplified model was run. In the first run, the K_c value was divided by 2 and used with the computed α value to estimate water yield. Simultaneously, the

Table 5. Rainfall, Runoff, and Sediment Yield for Mine Haul Road Rainulator Experiments.

Site	Rainfall (in/hr)	Rainfall Duration (min)	Water Yield (ft ³)	Peak Discharge (ft ³ /sec)	Runoff Duration (min)	Sediment Yield (lbs)
C1-1	1.596	14	74.15	.14	15	112.6
D2-2	1.806	10	42.76	.12	15	27.94
D2-3	1.806	20	108.82	.11	24	82.65
S1-1	2.208	17	85.11	.16	20	35.59
S3-1	1.854	10	68.73	.16	11	29.59
S3-2	1.818	37	250.47	.13	48	177.30
SG2-1	1.59	14	38.94	.09	19	6.95

sediment yield was computed using an overland flow detachment coefficient (D_{of}) of 1.0. If the detachment coefficient was 1.0, it was assumed the flowing water could carry a capacity sediment load. This implied a readily available sediment supply. A detachment coefficient of 1.0 was initially used to give a starting point at which to begin adjusting D_{of} values to match the measured yield and to determine if the predicted overland flow was capable of carrying the measured sediment yield. If the predicted and measured water yields were reasonably close in value and the D_{of} value was 1.0, the predicted sediment yield should be approximately greater than or equal to the measured yield. Predicted yield values less than measured yield indicate a possible data error or that the model is not appropriate for application to that set of data. Initial predicted water yields using a hydraulic conductivity equal to one-half K_c and the estimated value for α were all within 30 percent of the measured yields as shown in Figure 8. The close correlation of the measured and predicted water yields, found by using rough estimates of the key infiltration parameters, validates the application of the Green and Ampt infiltration equation as formulated in the simplified and complex model. No further parameter adjustment was performed to produce infiltration parameters that yielded more accurate results. Instead, the model was run with $D_{of} = 1.0$ to examine the sediment yield predictions for the natural sites. As anticipated, the estimated yields were greater than those measured. In order to adjust the D_{of} so the predicted yields approached the measured yields, another set of estimates at a different D_{of} was needed. The relationship between D_{of} and predicted sediment

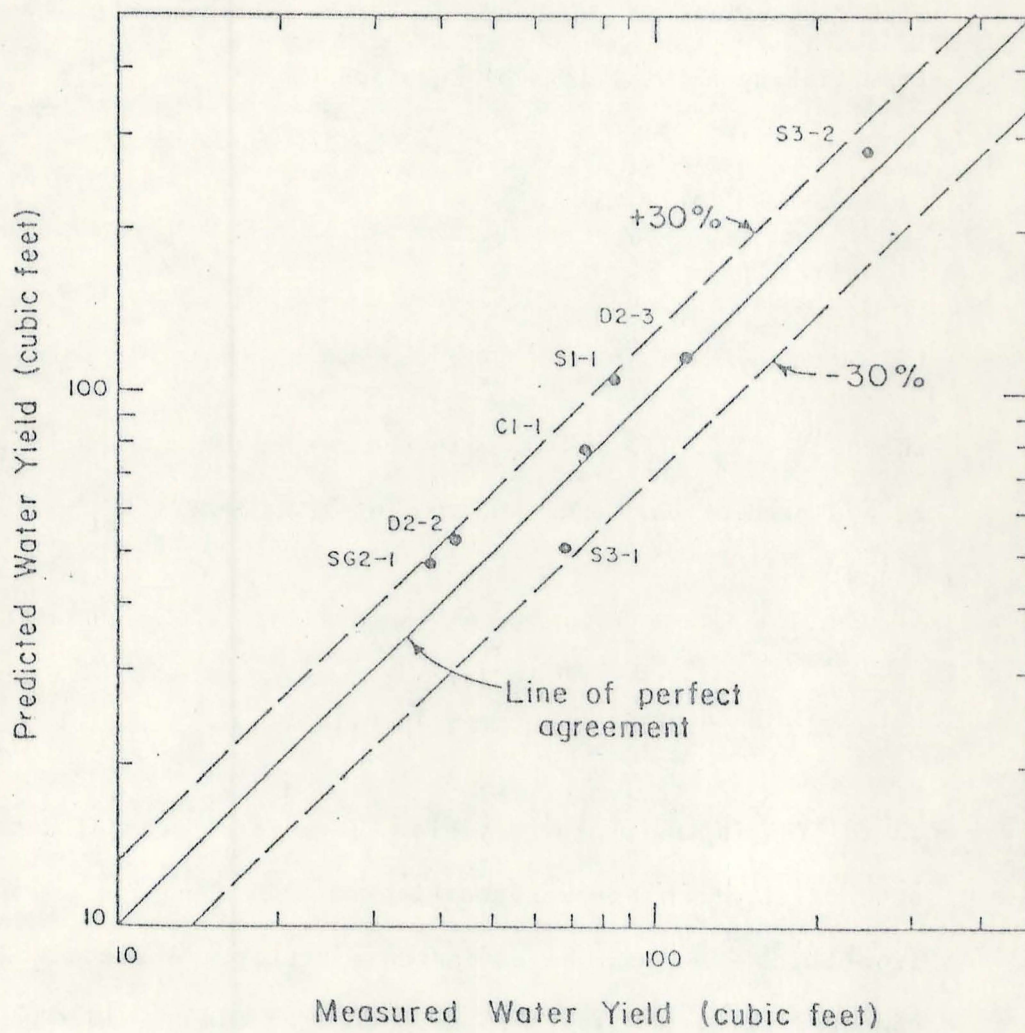


Figure 8. Predicted water yield compared to measured water yield using one half of rate difference as K_w .

yield at a specific water yield can be represented as a power relationship of the form

$$Y = a D^{b_{\text{of}}} \quad (6)$$

where Y is yield, D is the D_{of} , and a and b are parameters. For the test data, Y and D_{of} are strongly correlated in this form. With two values of Y and D_{of} the b parameter can be estimated from (taking natural logs of Equation 6)

$$b = \frac{\ln \left(\frac{Y_1}{Y_2} \right)}{\ln \left(\frac{D_1}{D_2} \right)} \quad (7)$$

where Y_1 , Y_2 , D_1 , and D_2 are the respective values for the first and second predictions. An estimate of the "best" D_{of} , D^* , can then be found as

$$D^* = \exp \left[\frac{\ln \left(\frac{Y^*}{Y_1} \right)}{b} + \ln D_1 \right] \quad (8)$$

where Y^* is the measured yield. If several sets of data for the same site exist, then a power equation such as Equation 6 can be developed from which D^* can be estimated directly. A second D_{of} value was computed using the approach suggested by Simons, Li, Ward, and Eggert (1978). In this approach the D_{of} is related to the K factor in the Universal Soil Loss Equation as

$$D_{\text{of}} = \frac{K (Ds)^2}{0.63} \quad (9)$$

where K is determined using a monograph approach with soil size distribution and other soil properties (Agricultural Research Service, 1975), and D_s is the representative soil size chosen as D_{50} . Values of D_{of} from Equation 9 were used to predict sediment yields based on the previously estimated water yields. Results showed that all predictions were within the same order of magnitude as the measured yields. This result is encouraging since it indicates there is validity in this approach of selecting D_{of} values. However, more effort needs to be expended in developing a better understanding of the relationship between the K factor and D_{of} . Comparison of the predicted sediment yields based on the computed D_{of} values indicates an average overprediction of about two times, with a range of predictions from eight times greater than to one-seventh of the measured value. The predictions for S3-1 and S3-2 were within four percent of the measured values based on the predicted water yields. The computed D_{of} values for run C1-1 resulted in an underprediction for the sediment yield. The adjusted D_{of} for C1-1 is 0.63. To produce better predictions the original D_{of} needed a slight upwards adjustment for runs D2-2 and D2-3. Runs S3-1 and S3-2 retained originally computed D_{of} values. Yields for runs S1-1 and SG2-1 were overpredicted using computed D_{of} values that needed to be considerably reduced in scale. The coarser sediments at these two sites may have a significant role in lowering the D_{of} value either by protection from erosion or by providing more flow resistance. Neither of these effects can be confirmed at this time. The adjusted D_{of} values are listed in Table 6, and a comparison of predicted and simulated sediment yields is shown in Figure 9. As Figure 9 shows, the estimated sediment yields are almost all

Table 6. Adjusted D_{of} values used to predict sediment yield.

Site	D_{of}
C1-1	.63
D2-2	.23
D2-3	.23
S1-1	.04
S3-1	.37
S3-2	.37
SG2-1	.26

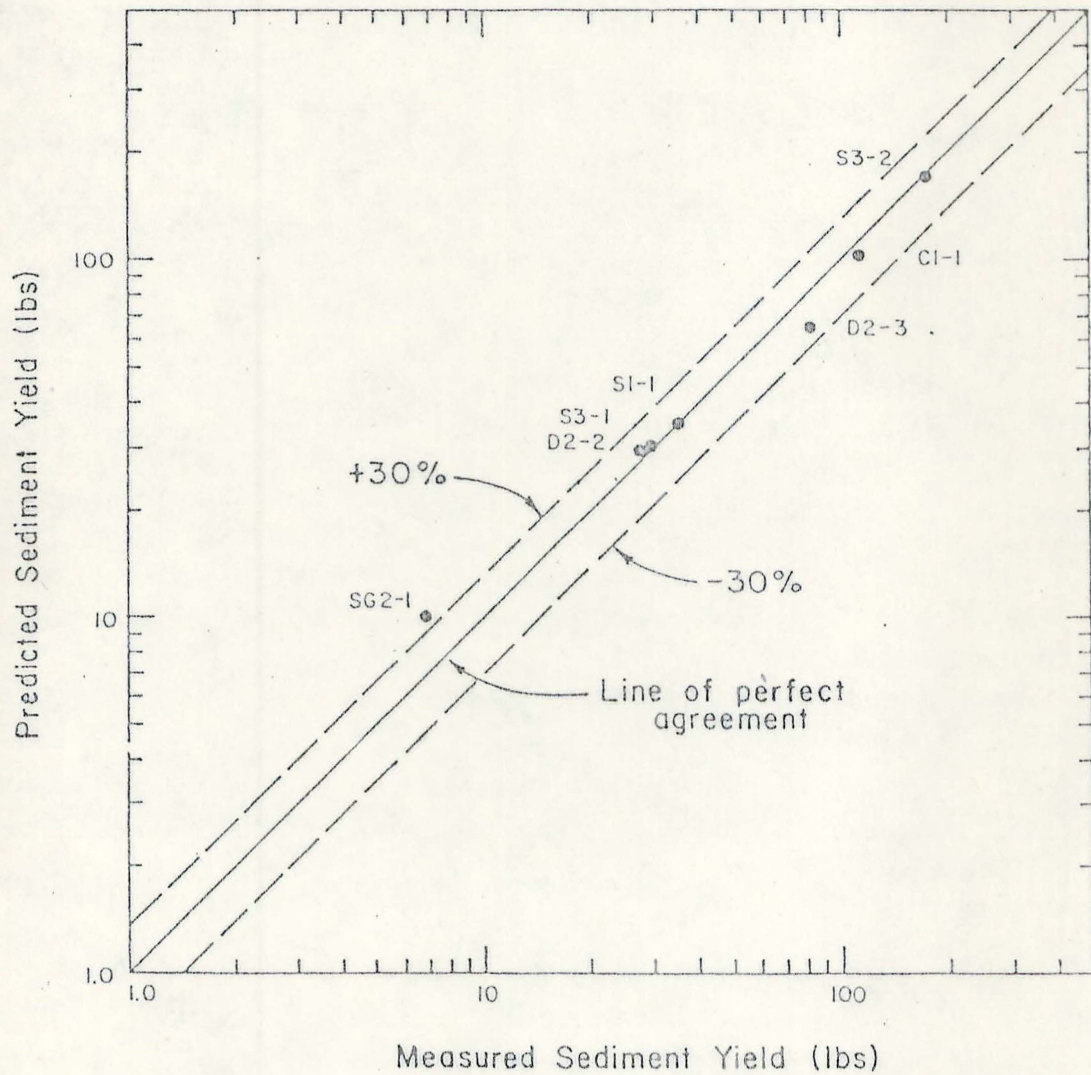


Figure 9. Predicted compared to measured sediment yield using adjusted runoff detachment coefficients and water yields as previously estimated.

within ± 30 percent of the measured as were the water yields. The closeness of these values helps verify that the model can realistically simulate water and sediment yields from roadways.

DESIGN APPLICATION

As examples of how ROSED may be used to estimate changes in water and sediment yield for different roadbed and slope conditions, two hypothetical cases were examined. In the first, the 4/2-3/77 storm was used to compute changes in yields with and without a gravel surface. Surfacing a road with gravel provides protection from raindrop impact and increases flow resistance and therefore erosive force of the overland flow. Table 7 lists the results of these comparisons for the two surface conditions. Although water yield remained about the same, sediment yield was reduced to about one-sixth the original value.

Table 7. Comparison of Water and Sediment Yields for Gravelled and Bare Roadbeds Yields

	without gravel	with 80% gravel cover	ratio of without to with
Water, ft ³	841	834	1.01
Sediment, lbs	615	93	6.61

The second example is a comparison between an outslope road with a cut slope, roadbed, and fill slope with and without ground covering. The cut and fill slopes were used with a sparse cover of 20 percent and a dense cover of 80 percent for the cut slope and 50 percent for the fill slope. The road was zero percent sparse and 80 percent dense. Geometry from segments 737, 738, and 739 was used. Table 8 lists the

Table 8. Comparison of Outslope Road Cover Conditions

segment	yields without cover	with cover	ratio of without to with yields
Cut slope			
Water ft ³	115	114	1.0
Sediment lbs	4930	419	11.8
Road surface			
Water	693	688	1.0
Sediment	1040	52	20.0
Fill slope			
Water	809	803	1.0
Sediment	4684	450	10.4

results of these comparisons for the outflow points of each segment. It should be noted that the water yield is additive but that sediment is controlled by many other factors. Although hypothetical examples, these two applications do indicate the potential use of the model.

SUMMARY AND CONCLUSIONS

Application and testing of water and sediment yield models can be hindered by acquisition of representative, error free data sets. Inherent variability of natural and simulated rainfall-runoff data often creates questionable if not physically inconsistent information. This report described the application of two road-sediment models to natural and simulated rainfall-runoff events from roadway surfaces. Results for the natural events are good considering the problems with the data, but are questionable because the data itself may be erroneous. Regardless model results matched measured results reasonably well. Application of the simplified model to simulated rainfall was very good because of better controls provided by the experimental procedures. Both applications demonstrated the usefulness of mathematical models in estimating water and sediment yields from roadways.

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